



CARLO GAVAZZI SPACE SpA

RICH SYSTEM

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2	13/06/2008	Atto aggiuntivo I/020/03/1 dated 30 th Jan 2008	- Applicable documents - Temperature requirements have been changed after thermal tests (section 4.1) Added following analysis: - LTA analysis (section 8.3) - Cooling down analysis (section 8.5) - Heaters failure analysis (section 8.6) - Switch on heaters (section 8.4) - PORON introduction investigation (section 9)



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ACRONYM LIST

AD	Applicable Document
BOL	Begin Of Life
CGS	Carlo Gavazzi Space
EOL	End Of Life
GMM	Geometrical Mathematical Model
I/F	Interface
ISS	International Space Station
MLI	Multi Layer Insulation
MPA	Minimum Propulsion Attitude
RD	Reference Document
TBC	To Be Confirmed
TBD	To Be Defined
TBW	To Be Written
TCS	Thermal Control Subsystem
TMM	Thermal Mathematical Model
TOF	Time Of Flight
TRP	Temperature Reference Point
w.r.t.	With respect to

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1. SCOPE

This document describes the thermal mathematical and geometrical models of ToF (Time of Flight), a subdetector included in AMS-02. These models were built to investigate the thermal behavior during all mission phases. Analysis results are presented as well.

This document includes all the agreed analysis with the customer as per Atto aggiuntivo I/020/03/1 dated 30th Jan 2008.

2. RELEVANT DOCUMENTS

The following documents are to be considered relevant to the ToF program.

2.1 APPLICABLE DOCUMENTS

AD	Doc.Number	Issue/Date	Rev.	Title/Applicability
AD 1	AMS02-TN-CGS-004	Issue3 19/05/2004		Preliminary thermal requirements for AMS-02 internal interfaces
AD 2	SSP57213			Alpha Magnetic Spectrometer (AMS-02) Hardware Interface Control Document (ICD)

2.2 REFERENCE DOCUMENTS

RD	Doc.Number	Issue/Date	Rev.	Title/Applicability
RD 1		28/04/2004		Fine mesh Thermovacuum Tests
RD 2	AMS02-RP-CGS-006	12/07/2004		Launch to Activation Thermal Analysis Report

3. PURPOSE

This report contains the description of the Thermal Mathematical Model (TMM) and the Geometrical Mathematical Model (GMM) developed to study the thermal behavior of Time Of Flight (TOF) detector and to perform the sizing of the following items:

- MLI layers definition;
- Heater patches ;

Steady state and transient thermal analysis have been performed using the SINDA/FLUINT network analyzer, to investigate the thermal behavior of the ToF subdetector installed on AMS-02, during the design orbital cases, considering worst hot and cold conditions, , properly selected by AMS-02 thermal team at system level.

A Thermal Mathematical Model has been generated, consisting of **885** nodes for the representation of the following items:

- Carbon fiber box (393 nodes)
- PMTs (492 nodes)

A Geometric Mathematical Model has been built up in RadCad to calculate radiative heat exchange on the basis of suitable thermo-optical properties.



4. REQUIREMENTS

4.1 TEMPERATURE REQUIREMENTS

The following temperatures are assumed as design limits for the ToF PMTs [AD 1]

Operating Range:	-30°C + +55°C
Non Operating Range:	-40°C + +60°C

5. THERMAL CONTROL CONCEPT

Due the low dissipation of the ToF (3.68W for the entire system) , a radiator is not the most effective solution. The percentage of the TOF bulk dissipation is little if compared with the external impinging heat fluxes , both UV and IR.

For this reason the temperature of a potential radiator shall not be driven by the inside coming dissipation but mostly from the external natural and induced environment.

The proposed thermal control concept is based on the detector completely covered by Multi Layer Insulation (MLI). The heat leakage through the layers is of the same order of the TOF bulk dissipation and this is the philosophy followed to reject out the dissipated power.

All the external surface of the carbon fiber box is covered with a 6 layer MLI blanket.

The 6 layers MLI insulation effectiveness performance has been modeled by means of an experimental array (provided by MLI supplier and shown in Fig. 5-1) giving the linear conductance per square meter of the MLI stack vs. the average temperature between the two out-facing layers .

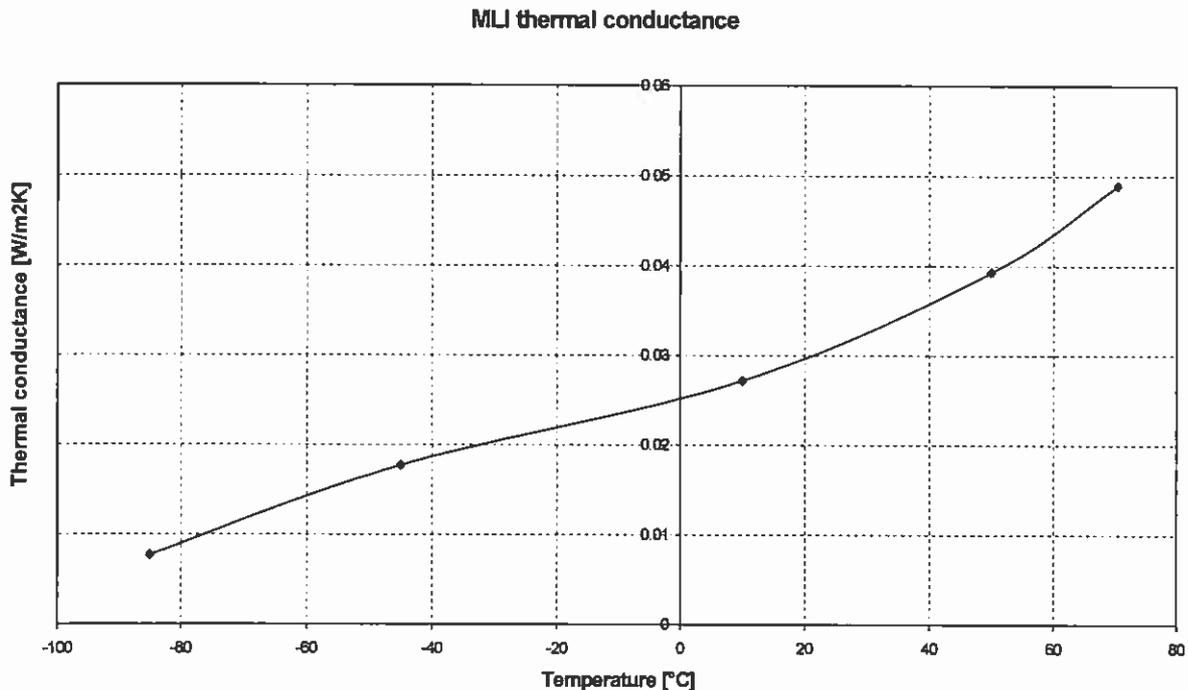


Fig. 5-1 MLI effective thermal conductance

The value obtained from the experimental curve has been then multiplied by a factor of 5, in order to take into account the performance degradation of MLI due to the fixation points and handling.

The external layer of MLI blanket is made of white Beta-cloth and its thermal optical properties both BOL and EOL are listed in the following table:

<i>Beta-cloth</i>	BOL (cold analysis)	EOL (hot analysis)
α	0.2	0.47
ϵ	0.9	0.86

Tab. 5-1 Beta-Cloth thermal optical properties

6. THERMAL LOADS

6.1 INTERNAL LOADS

Totally 3.68W are dissipated on 76 PMTs (48.4mW each).

The dissipation of the PMT electronics is located on the central board (10.8mW) and on the inner board (37.6mW).

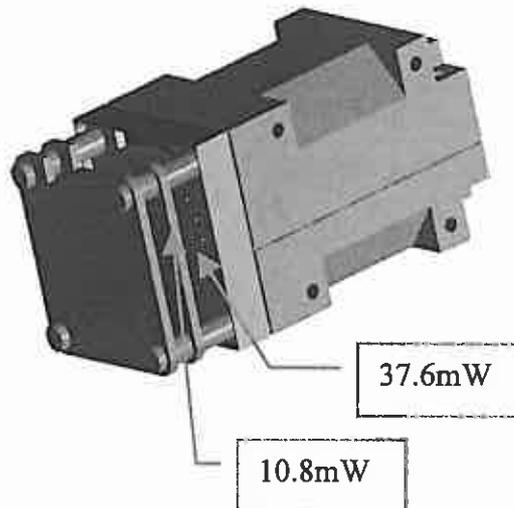


Fig. 6-1 PMT dissipation sharing

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6.2 EXTERNAL LOADS

TOF is located in AMS-02 experiment , which experiences typical external ISS payloads environmental conditions. In particular, ISS orbiting in its Low Earth Orbit experiences typical fluxes of LEO satellites:

- Solar visible radiation
- Albedo (given by the fraction of the Sun energy diffusely reflected by Earth)
- Infrared Earth contribution.

TOF location makes it subjected not only to these direct impinging fluxes, but also to reflections of the aforementioned contributions by other ISS elements.

TOF impinging heating rates, radiative links and sink temperatures have been generated at system level by AMS-02 thermal team.

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7. THERMAL MODELLING

7.1 PHYSICAL PROPERTIES

7.1.1 MATERIALS AND MATERIAL PROPERTIES

The following table shows the main TOF materials and the conductivities used in the thermal mathematical model:

Component	Material	Specific Heat [J/kg/K]	Conductivity [W/m/K]
External box	Carbon Fiber	500	200
Brackets	Plexiglass	1297	0.15

Tab. 7-1 Summary of used materials

The dependence from temperature of the above mentioned quantities has been neglected.

7.1.2 CONTACT CONDUCTANCE

The following values have been used to introduce in the model the thermal joint conductance between different parts:

- **1000 W/m²K** : contact conductance between PMTs and Plexiglas bracket
- **300 W/m²K** : contact conductance between Plexiglas bracket and carbon fiber box

obtained as results of experimental test activities.

7.2 THERMAL MATHEMATICAL MODEL

The main division in thermal submodels (used in SINDA code) is listed in the following table:

SUBMODEL NAME	DESCRIPTION	NUMBER OF NODES
BOX	Central part of the carbon fiber boxes	53
BOX1	RAM side of the carbon fiber box	109
BOX2	WAKE side of the carbon fiber box	109
BOX3	STARBOARD side of the carbon fiber box	61
BOX4	PORT side of the carbon fiber box	61
PMT1	PMTs of BOX1	120
PMT2	PMTs of BOX2	120
PMT3	PMTs of BOX3	126
PMT4	PMTs of BOX4	126
Total number of nodes		885

Tab. 7-2 Submodel lists and number of nodes

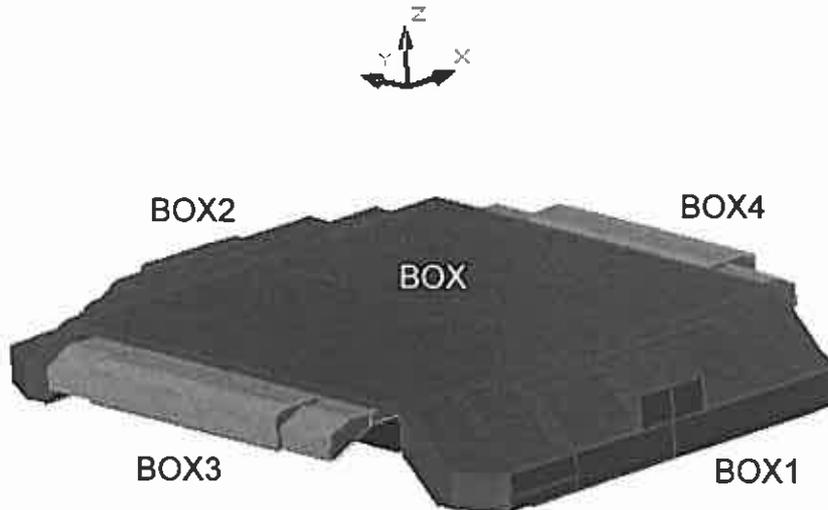


Fig. 7-1 Submodels in AMS-02 coordinate system

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7.2.1 BOX1 AND BOX2 NODAL BREAK-DOWN

Sub-models BOX1 and BOX2 are respectively located on the RAM and WAKE side and they have the same nodal break-down.

The inner part of the carbon fiber box is , from the optical point of view, reflective while the external part is covered with MLI blankets. The external layer of MLI blanket is made of Beta-cloth and its thermal optical properties both BOL and EOL are listed in

Tab. 7-3.

The nodes included in the model are listed in the following table, with their properties:

NODE NUMBER	DESCRIPTION	ϵ BOL	α BOL	ϵ EOL	α EOL
101÷124	Box walls (inner side)	0.05	-	0.05	-
151÷174					
3101÷3124	MLI (outer layer)	0.9	0.22	0.86	0.47
3151÷3174					
1000÷1009	PMT supports	0.05	-	0.05	-

Tab. 7-3 BOX1 and BOX2 nodes numbering

7.2.2 BOX3 AND BOX4 NODAL BREAK-DOWN

Submodels BOX3 and BOX4 are respectively located on the STARBOARD and PORT side and they have the same nodal breakdown.

The inner part of the carbon fiber box is reflective while the external part is covered with MLI blankets. The external layer of MLI blanket is made of white Beta-cloth and its thermal optical properties both BOL and EOL are listed in Tab. 7-4.

The nodes included in the model are listed in the following table, with their properties:

NODE NUMBER	DESCRIPTION	ϵ BOL	α BOL	ϵ EOL	α EOL
101-102	Box walls (inner side)	0.05	-	0.05	-
104÷114					
117-118					
151-152					
154÷164					
167-168					
3101-3102	MLI (outer side)	0.9	0.22	0.86	0.47
3104÷3114					
3117-3118					
3151-3152					
3154÷3164					
3167-3168					

Tab. 7-4 BOX3 and BOX4 nodes numbering

7.2.3 BOX NODAL BREAK-DOWN

This submodel contains the central part of the two different carbon fiber boxes. The external part of the carbon fiber box is covered with MLI blankets, while the inner part is inactive, since the radiation between the inner box and the scintillator fibers is negligible. The external layer of MLI blanket is made of white Beta-cloth and its thermal optical properties both BOL and EOL are listed in Tab. 7-5.

The nodes included in the above mentioned model are listed in the following table, with their properties:

NODE NUMBER	DESCRIPTION	ϵ BOL	α BOL	ϵ EOL	α EOL
11+14 21+24	Box walls (inner side)	0.05	-	0.05	-
33-43 41-51					
311-312					
333-343 341-351	MLI (outer side)	0.9	0.22	0.86	0.47

Tab. 7-5 BOX nodes numbering

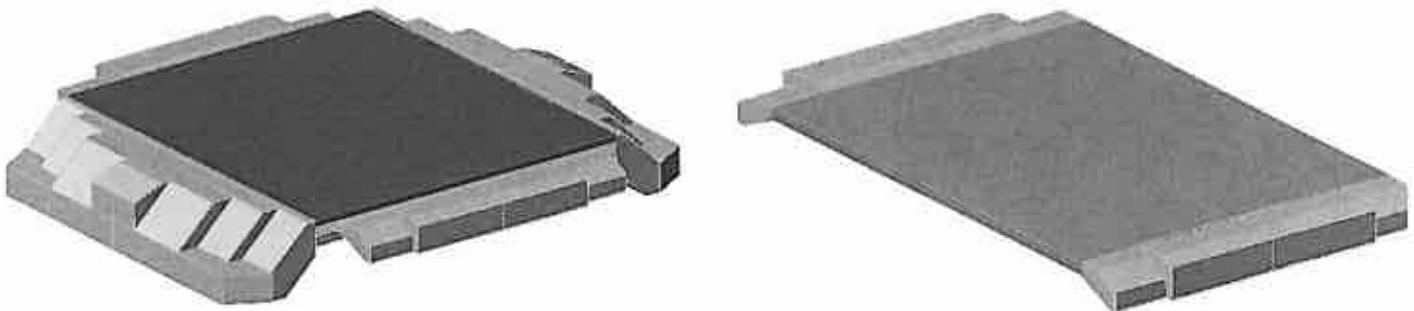


Fig. 7-2 BOX submodel

7.2.4 PMTS

7.2.4.1 PMT1 AND PMT2 NODAL BREAK-DOWN

Twenty different PMT assemblies are included in PMT1 and PMT2 submodels. They're the PMTs included in the RAM and WAKE side of the carbon fiber box, BOX1 and BOX2 respectively. The following image shows the PMTs disposition inside the BOX1:

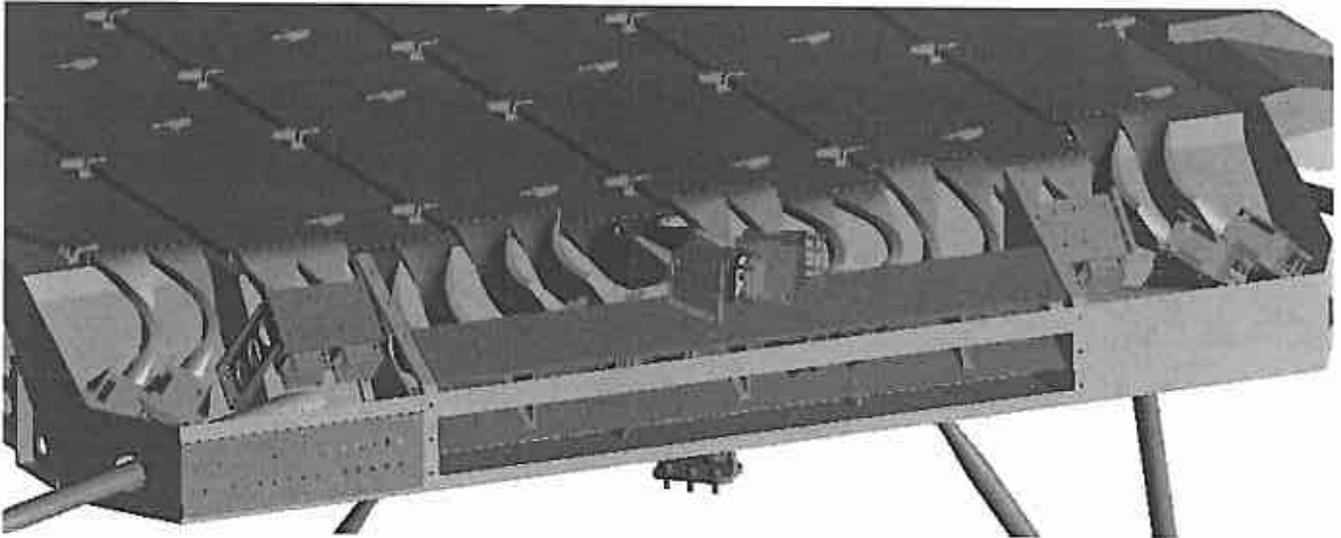


Fig. 7-3 PMTs in RAM direction. WAKE disposition is symmetric

For each PMT package the following nodal break-down has been implemented and the node numbering is listed in the following table:

PMTs nodes included in the model are listed in the following table, with their properties (see also Fig. 7-4):

NODE NUMBER	DESCRIPTION	MATERIAL	ϵ BOL	ϵ EOL	THERMAL CAPACITANCE [J/°C]	DISSIPATION [W]
x1	PMT case	polycarbonate	0.85	0.85	98.4	-
x2	Central electronic board	Cu+FR4	0.7	0.7	2.22	0.0108
x3	Outer electronic board					-
x4	Inner electronic board					0.0376
x5	PMT	-	-	-	arithmetic	-
x9	Bracket	Plexiglass	-	-	43.8	-

Tab. 7-6 PMTs nodes numbering

The first digit in node's ID number (x in the table) indicates PMT's number (x=1, 2, ..., 20)



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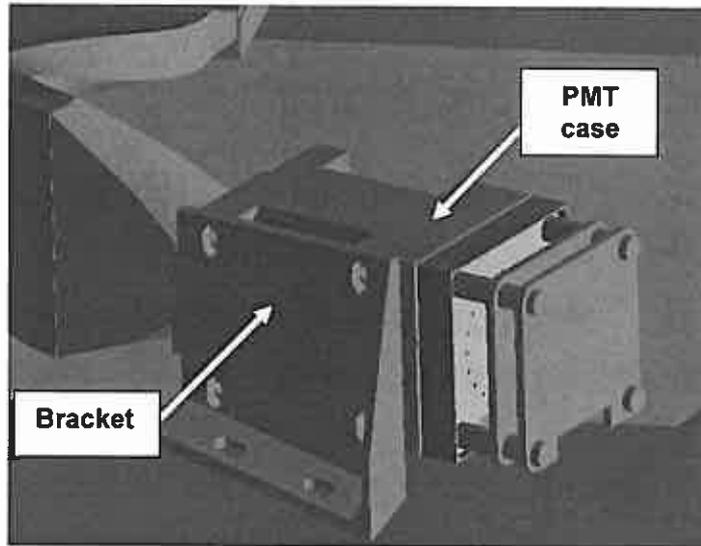


Fig. 7-4 PMT and bracket in RAM and WAKE direction

7.2.4.2 PMT3 AND PMT4 NODAL BREAK-DOWN

Eighteen different PMT assemblies are included in PMT3 and PMT4 submodels. They're the PMTs included in the STARBOARD and PORT side of the carbon fiber box, BOX3 and BOX4 respectively. The following image shows the PMTs disposition inside the BOX3:

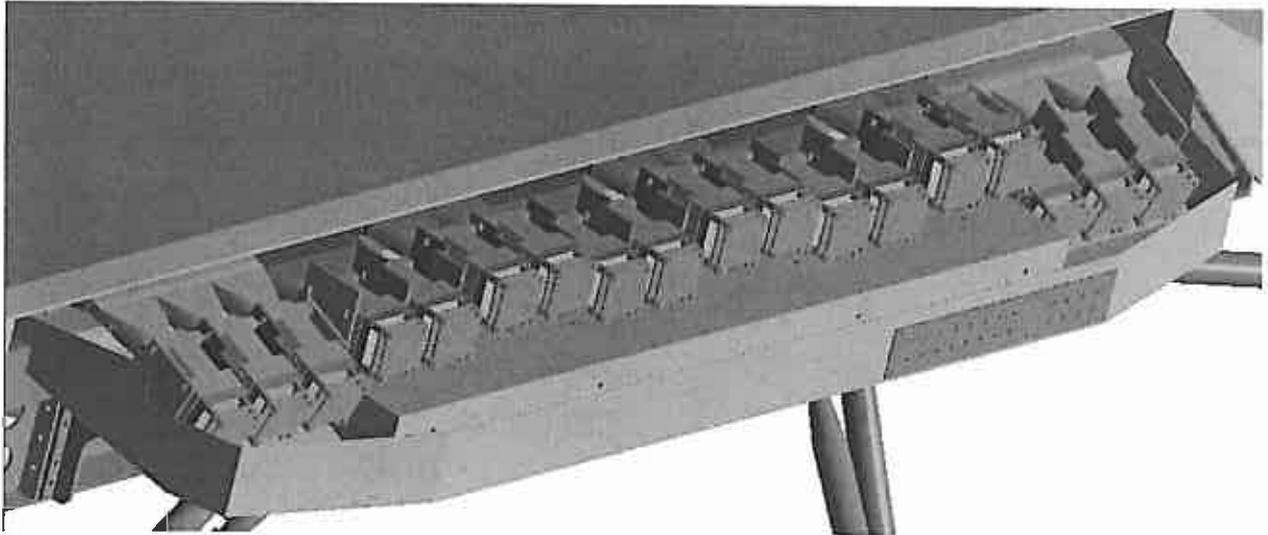


Fig. 7-5 PMTs in STARBOARD direction. PORT disposition is symmetric

For each PMT package the following nodal break-down has been implemented and the node numbering is listed in the following table (see also Fig. 7-6):

NODE NUMBER	DESCRIPTION	MATERIAL	ϵ BOL	ϵ EOL	THERMAL CAPACITANCE [J/°C]	DISSIPATION [W]
x1	PMT case	polycarbonate	0.85	0.85	98.4	-
x2	Central electronic board	Cu+FR4	0.7	0.7	2.22	0.0108
x3	Outer electronic board					-
x4	Inner electronic board					0.0376
x5	PMT	-	-	-	arithmetic	-
X8	Bracket	Plexiglass	-	-	10.3	-
x9	Bracket					-

Tab. 7-7 PMTs nodes numbering

The first digit in node's ID number (x in the table) indicates PMT's number (x=1, 2, ..., 18)



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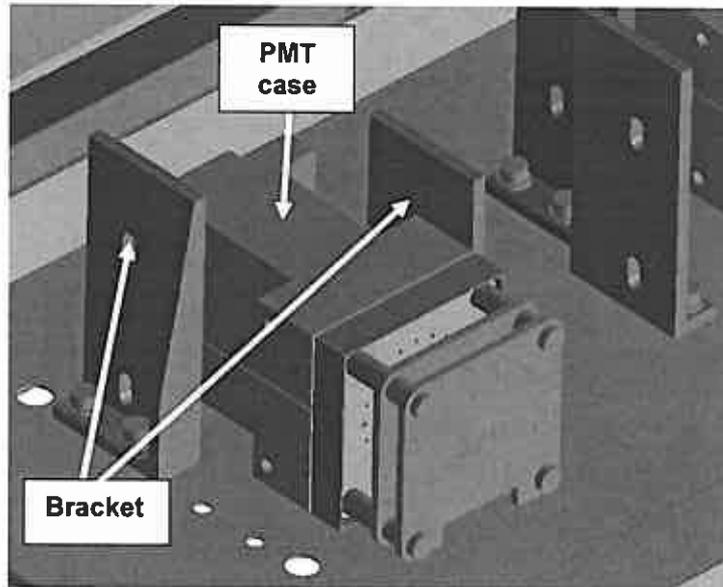


Fig. 7-6 PMT and brackets in STARBOARD and PORT direction

7.3 GEOMETRIC MATHEMATICAL MODEL

A geometric mathematical model has been developed to calculate the inner radiative coupling among the different surfaces of the box, the PMTs and the brackets and to calculate the outer coupling among the MLI and the external environment.

The RADKS number has been limited choosing a cutoff fraction of 0.001: all the radiative links with a view factor lower than this amount have been neglected.

The following images show the geometric models of the relevant different parts:

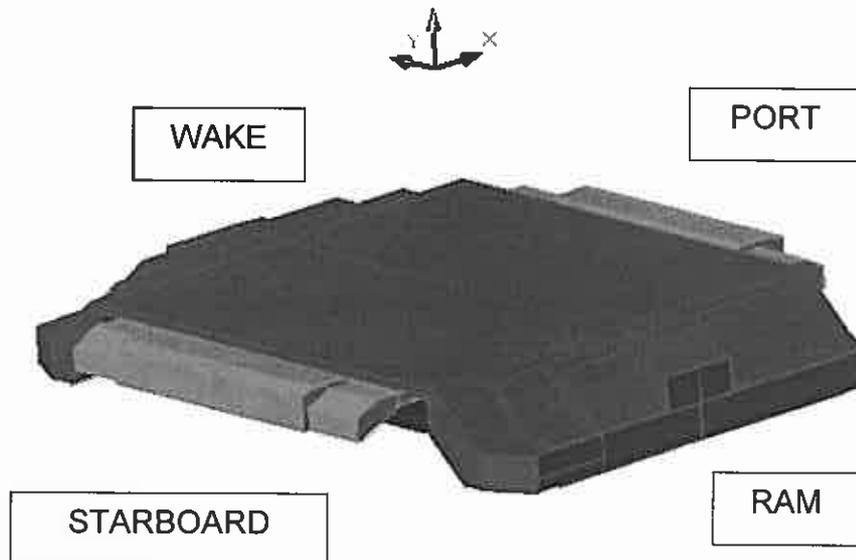


Fig. 7-7 View of the geometrical model of ToF

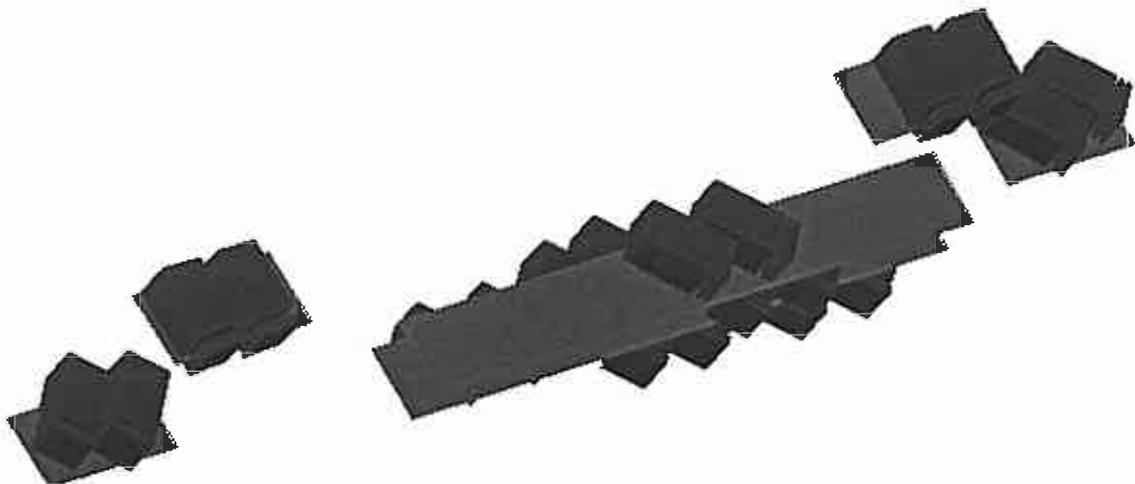


Fig. 7-8 View of the geometrical model of the PMTs and their supports in BOX1(RAM). WAKE disposition is symmetric

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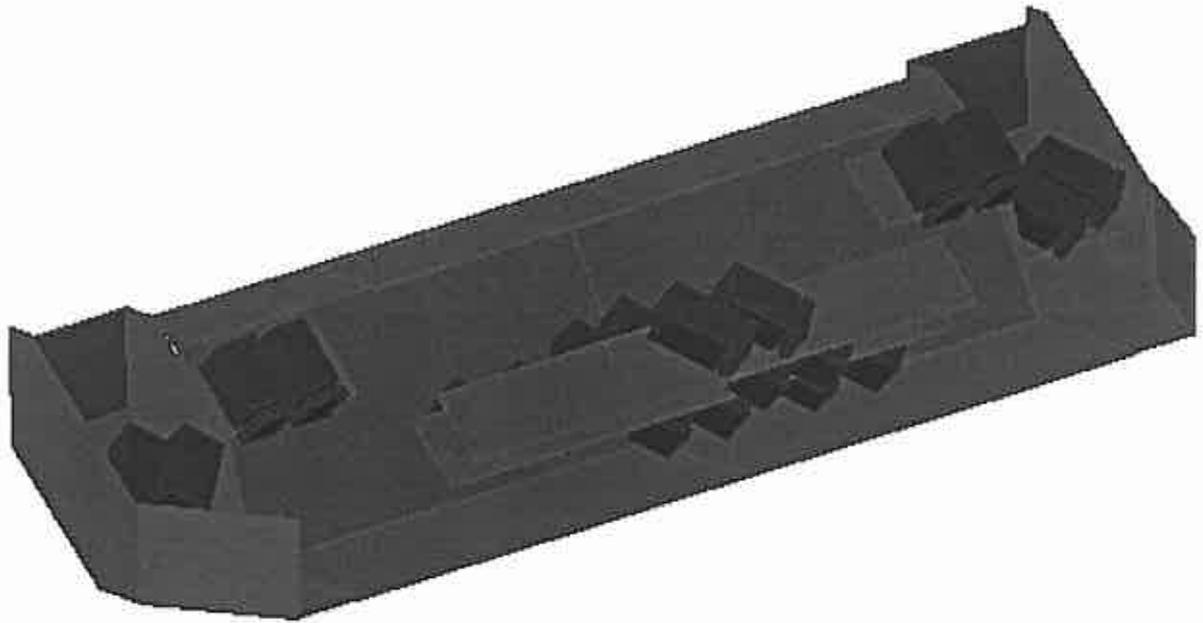


Fig. 7-9 View of the geometrical model of the PMTs and supports in BOX1(RAM). WAKE disposition is symmetric.

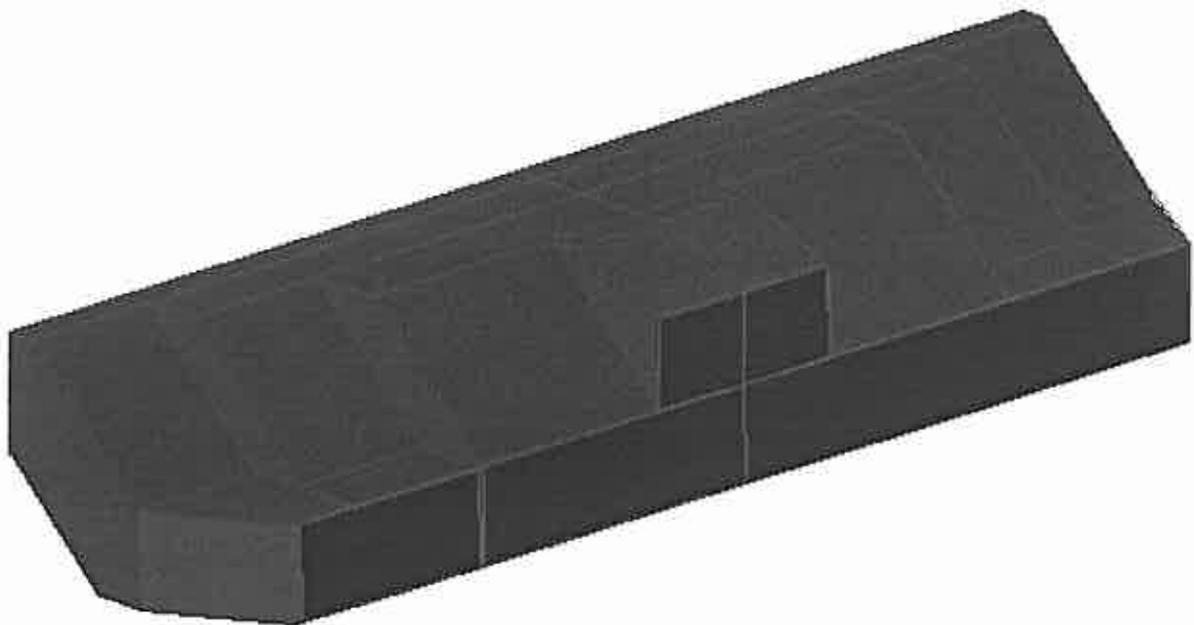


Fig. 7-10 View of the geometrical model of BOX(RAM). WAKE is symmetric



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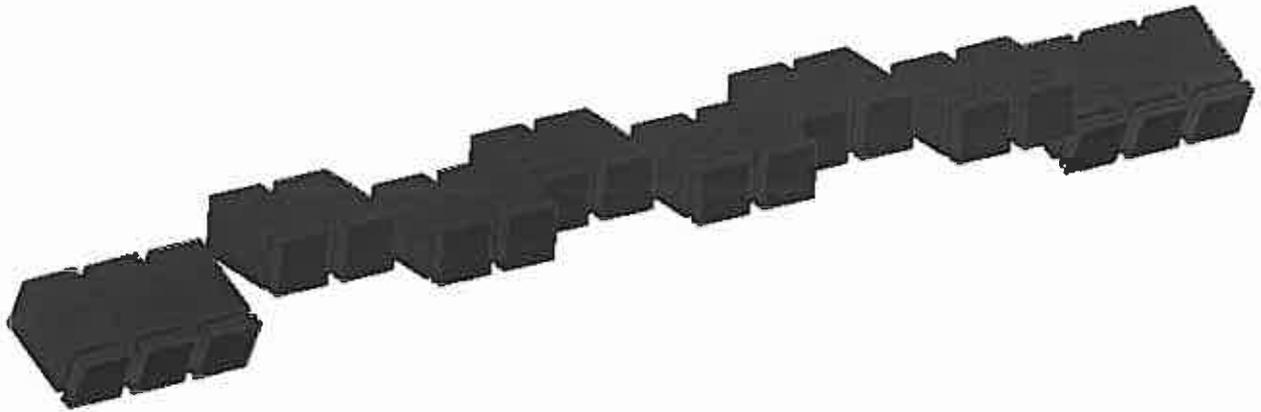


Fig. 7-11 View of the geometrical model of the PMTs in BOX3 (STARBOARD). PORT disposition is symmetric.

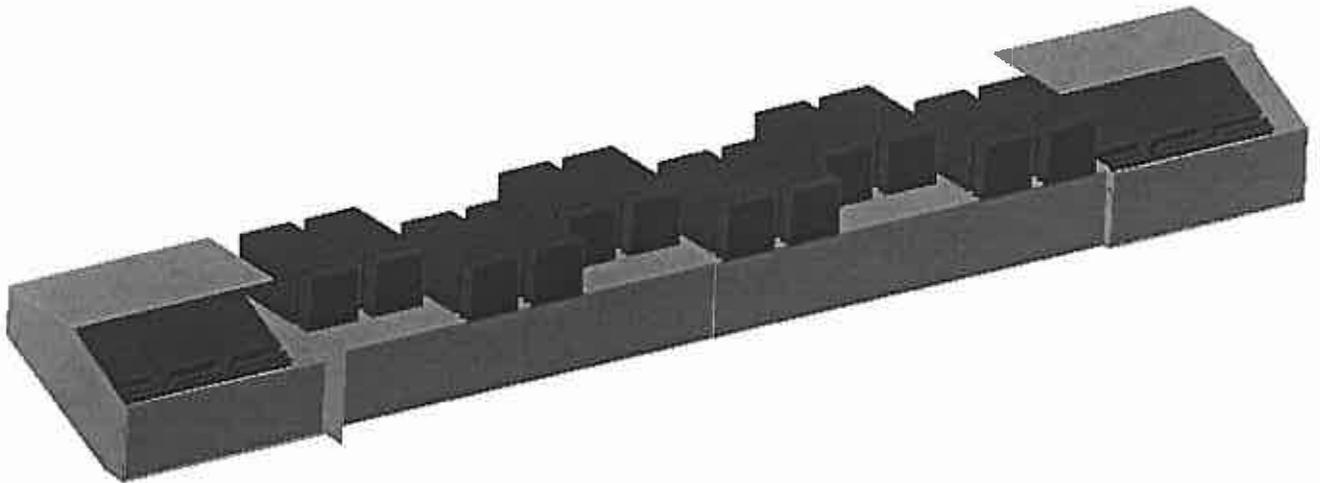


Fig. 7-12 View of the geometrical model of BOX3 (STARBOARD). PORT disposition is symmetric.

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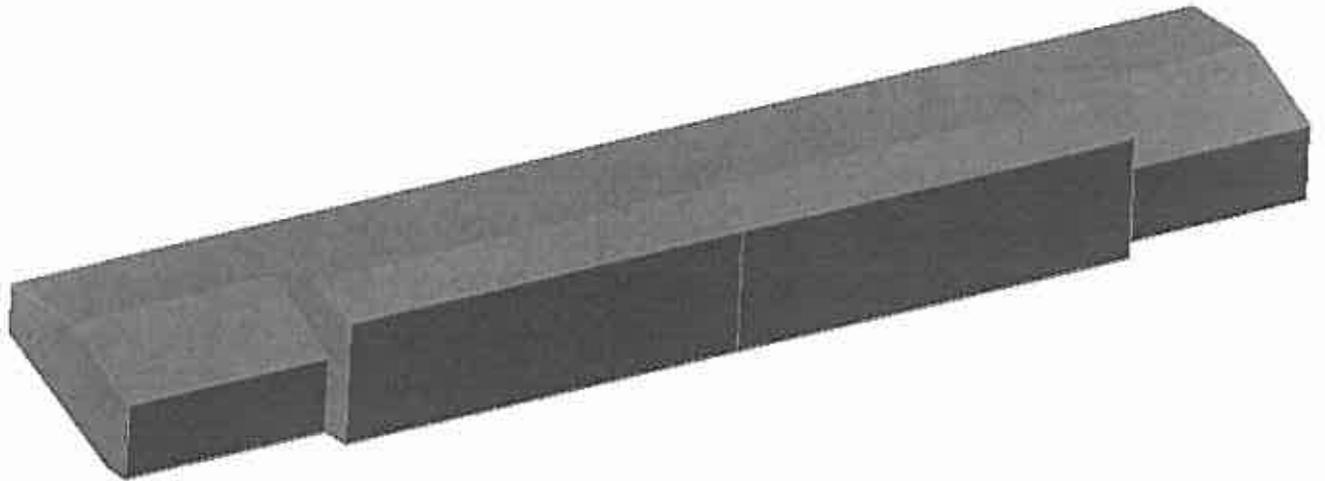


Fig. 7-13 View of the geometrical model of BOX3 (STARBOARD). PORT is symmetric.

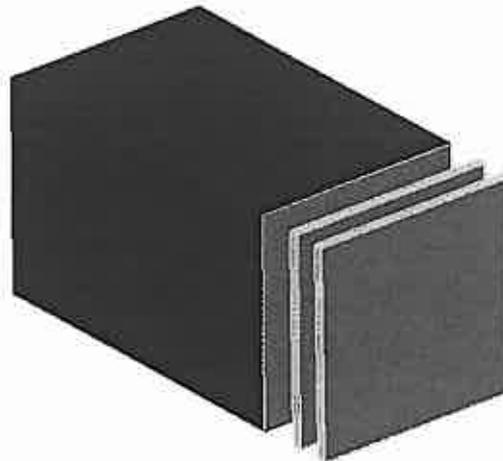


Fig. 7-14 View of the geometrical model of a PMT.

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8. ANALYSIS RESULTS

In the following sections the results of the thermal analysis are presented for hot and cold design cases.

The analysis has been performed using I/F thermal data , hot and cold, properly selected by AMS-02 thermal team at system level

I/F thermal data are constituted of :

- Sink temperatures for each of the external facing surfaces
- Impinging heat fluxes (absorbed) for each of the external facing surfaces
- Radiative links between each of the external facing surfaces and sink nodes
- Conductive I/F temperatures for mechanical interfaces

I/F data set are mainly related to the Minimum Propulsion Attitude (MPA) of the International Space Station, characterized by a yaw angle of -2° , a pitch angle of -10° and a roll angle of $+1^\circ$. This attitude minimizes, when the Space Shuttle is docked to the ISS, the propellant needed to maintain the orbit, vs. the drag forces of the residual atmosphere.

Worst cold and hot thermal interfaces , related to less probable but possible ISS attitude, have been generated by the system as well.

All these I/F data have been used for detailed TOF thermal analysis.

The PMTs temperatures results are shown in Tab. 8-2 in the following way:

$$\bar{x} \pm \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2}$$

where \bar{x} is the maximum temperature results of the PMTs in each box during the orbit and N is the number of temperature point considered.

The coordinate system used in the table is the following one:

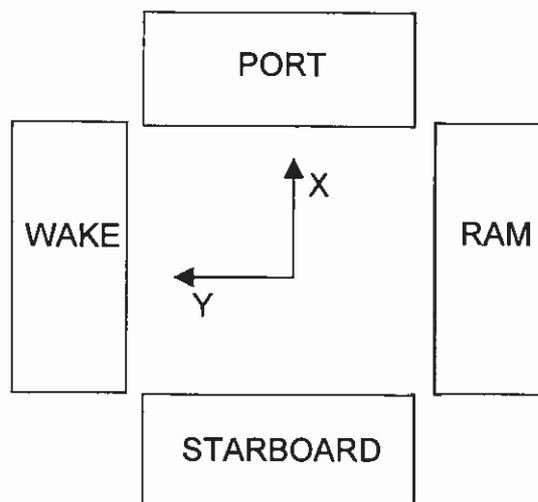


Fig. 8-1 Coordinate system for the presentation of the analysis results



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8.1 HOT CASES

A thermal analysis has been performed in the hot conditions to verify that during the hot operative/non operative phases the temperatures of ToF PMTs are kept below their maximum design operative/non operative limits (namely +55°C/+60°C).

Beta angle	Yaw angle	Pitch angle	Roll angle	Power
-75	-2	-10	+1	ON OFF
-70	-2	-10	+1	ON OFF
-60	-2	-10	+1	ON OFF
-50	-2	-10	+1	ON
0	-2	-10	+1	ON
50	-2	-10	+1	ON
60	-2	-10	+1	ON
70	-2	-10	+1	ON
75	-2	-10	+1	ON
-75	-15	+15	-15	ON OFF
-60	-15	-20	-15	ON
-60	-15	15	0	ON

Tab. 8-1 Orbit parameters for hot cases

The last orbits in Tab. 8-1 have an attitude different from the MPA one; it was selected as a worst hot case from AMS-02 thermal team at system level.

The last column shows the AMS-02 subdetectors power condition:

→ ON: all AMS-02 subdetectors are ON

→ OFF: all AMS-02 subdetectors are ON but for TOF, RICH, ECAL, R-crate, E-crate, REPD.

The following table shows the obtained results for the critical orbits.

Beta-75 MPA ON	60.2°C ±0.3°C
	57.5°C ±0.4°C
	57.6°C ±0.4°C
	60.6°C ±0.3°C



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Beta-75 MPA OFF	<p>50.1°C ±0.1°C</p> <p>50.9°C ±0.2°C</p> <p>50.8°C ±0.2°C</p> <p>51.4°C ±0.1°C</p>
Beta-70 MPA ON	<p>52.2°C ±0.3°C</p> <p>49.2°C ±0.4°C</p> <p>49.6°C ±0.4°C</p> <p>52.4°C ±0.4°C</p>
Beta-70 MPA OFF	<p>41.4°C ±0.1°C</p> <p>42.2°C ±0.1°C</p> <p>42.2°C ±0.2°C</p> <p>42.6°C ±0.1°C</p>



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Beta-60 MPA ON	<p>41.0°C ±0.4°C</p> <p>37.5°C ±0.5°C</p> <p>38.0°C ±0.4°C</p> <p>40.9°C ±0.4°C</p>
Beta-75-15+15-15 ON	<p>61.9°C ±0.3°C</p> <p>59.4°C ±0.4°C</p> <p>59.2°C ±0.3°C</p> <p>62.2°C ±0.3°C</p>
Beta-75-15+15-15 OFF	<p>51.8°C ±0.1°C</p> <p>52.9°C ±0.1°C</p> <p>52.3°C ±0.2°C</p> <p>53.1°C ±0.1°C</p>



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Beta-60-15-20-15 ON	<p>Diagram showing temperature predictions for Beta-60-15-20-15 ON. The diagram consists of four rectangular boxes arranged in a diamond shape. The top box contains $50.2^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$. The bottom box contains $48.8^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$. The left box contains $47.7^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$. The right box contains $47.4^{\circ}\text{C} \pm 0.2^{\circ}\text{C}$.</p>
Beta-60-15_15_0 ON	<p>Diagram showing temperature predictions for Beta-60-15_15_0 ON. The diagram consists of four rectangular boxes arranged in a diamond shape. The top box contains $34.8^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$. The bottom box contains $33.6^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$. The left box contains $31.4^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$. The right box contains $31.5^{\circ}\text{C} \pm 0.2^{\circ}\text{C}$.</p>

Tab. 8-2 Temperature predictions for PMTs in hot operative/non operative cases

8.2 COLD CASES

A thermal analysis has been performed in the cold conditions to verify that during the cold operative/non operative phases the temperatures of ToF PMTs are kept above their minimum design operative/non operative limits (namely $-30^{\circ}\text{C}/-40^{\circ}\text{C}$).

Beta angle	Yaw angle	Pitch angle	Roll angle	Power
0	-2	-10	+1	ON OFF
0	0	0	-15	ON OFF
25	-15	-20	-15	ON OFF

Tab. 8-3 Orbit parameters for cold cases

For the cold cases the analysis has been limited to the coldest case between the MPA orbits and to two extreme cold orbit selected by AMS-02 thermal team at system level.

The last column shows the AMS-02 subdetectors power condition:

→ ON: all AMS-02 subdetectors are ON

→ OFF: all AMS-02 subdetectors are OFF but the heaters that guarantee the minimum non operative temperatures for the AMS-02 system.

The following table shows the obtained results using the coordinate system shown in Fig. 8-1.



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Beta_0_0_0-15 ON	<p>-5.2°C ±0.6°C</p> <p>-10.4°C ±0.8°C</p> <p>-10.3°C ±0.8°C</p> <p>-7.5°C ±0.7°C</p>
Beta_0_0_0-15 OFF	<p>-25.6°C ±0.1°C</p> <p>-25.6°C ±0.1°C</p> <p>-25.6°C ±0.1°C</p> <p>-25.7°C ±0.1°C</p>
Beta_0_MPA ON	<p>-4.2°C ±0.6°C</p> <p>-10.2°C ±0.8°C</p> <p>-9.5 °C ±0.8°C</p> <p>-5.2°C ±0.7°C</p>



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<p>Beta_0_MPA OFF</p>	<div style="display: flex; flex-direction: column; align-items: center;"> <div style="border: 1px solid black; padding: 5px; margin-bottom: 10px;">$-22.1^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$</div> <div style="display: flex; justify-content: space-between; width: 100%;"> <div style="border: 1px solid black; padding: 5px; width: 20%;">$-22.1^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$</div> <div style="border: 1px solid black; padding: 5px; width: 60%;"></div> <div style="border: 1px solid black; padding: 5px; width: 20%;">$-22.1^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$</div> </div> <div style="border: 1px solid black; padding: 5px; margin-top: 10px;">$-22.2^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$</div> </div>
<p>Beta_25-15-20-15 ON</p>	<div style="display: flex; flex-direction: column; align-items: center;"> <div style="border: 1px solid black; padding: 5px; margin-bottom: 10px;">$-9.0^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$</div> <div style="display: flex; justify-content: space-between; width: 100%;"> <div style="border: 1px solid black; padding: 5px; width: 20%;">$-12.3^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$</div> <div style="border: 1px solid black; padding: 5px; width: 60%;"></div> <div style="border: 1px solid black; padding: 5px; width: 20%;">$-12.0^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$</div> </div> <div style="border: 1px solid black; padding: 5px; margin-top: 10px;">$-6.9^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$</div> </div>
<p>Beta_25-15-20-15 OFF</p>	<div style="display: flex; flex-direction: column; align-items: center;"> <div style="border: 1px solid black; padding: 5px; margin-bottom: 10px;">$-23.2^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$</div> <div style="display: flex; justify-content: space-between; width: 100%;"> <div style="border: 1px solid black; padding: 5px; width: 20%;">$-23.3^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$</div> <div style="border: 1px solid black; padding: 5px; width: 60%;"></div> <div style="border: 1px solid black; padding: 5px; width: 20%;">$-23.2^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$</div> </div> <div style="border: 1px solid black; padding: 5px; margin-top: 10px;">$-23.8^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$</div> </div>

Tab. 8-4 Temperature predictions for PMTs in cold operative/non operative cases

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8.3 LAUNCH TO ACTIVATION ANALYSIS

In this section we will describe the thermal performance of the TOF detector in the following off-nominal cases:

- AMS-02 in the STS free flying
- AMS-02 in the STS docked to the ISS
- Transfer phase from STS to ISS
- Switch on sequence
- Cooling down during a power off scenario
- Heaters failure

Since a single line of heaters is available, the scope of the investigation is to find the most challenging conditions and to size the heaters accordingly. Once the power and the set point is determined, these heaters will operate at the nominal power dissipation whenever needed.

The scope of this section is the dimensioning of the heaters to keep the system above its lower temperature limits (minimum non-operative, minimum operative and minimum switch on temperatures, according to the considered phase).

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8.3.1 AMS ON STS FREE FLYING

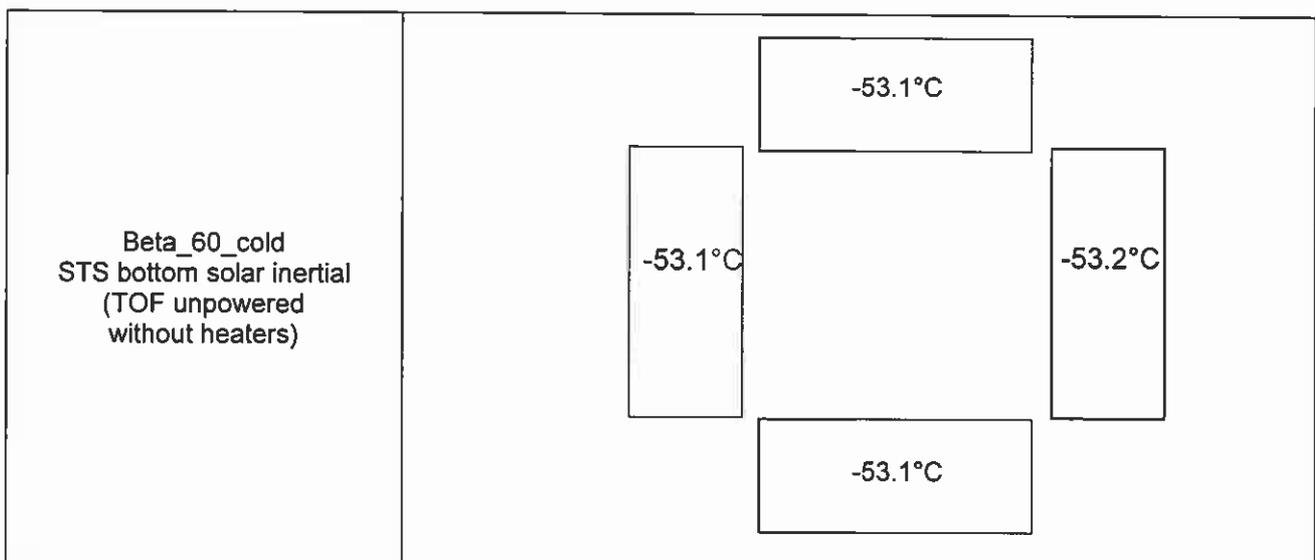
At system level, it was evaluated which is the most demanding orbital conditions for the TOF during the flight on the Space Transportation System (STS), namely during the Space Shuttle flight. The coldest orbit is Beta=60° Bottom solar inertial.

The AMS configuration is the following.

- AMS mounted in the STS
- Coldest configuration
- TOF power OFF
- AMS power almost OFF (but the other heaters and the electronics needed to drive them)

The target is to keep the system above the MINIMUM NON OPERATIVE temperature on all the TOF PMTs.

According to the I/F data provided by the system, the minimum PMTs temperatures are shown in the following table, using the coordinate system shown in Fig. 8-1.



Tab. 8-5 Temperature predictions for PMTs in STS free flying worst cold condition (TOF unpowered without heaters)

When the detector is completely switched off a minimum temperature of -53.2°C is reached on the coldest PMT.

The best heaters location is a symmetrical one, with heaters on the internal side of each box. Since the minimum survival temperature is -40°C , **10 W are needed** to keep the system above that temperature in these conditions. The temperature map after the heaters application is reported in Tab. 8-6. An iterative process between subsystem and system level was needed in order to size the heaters.



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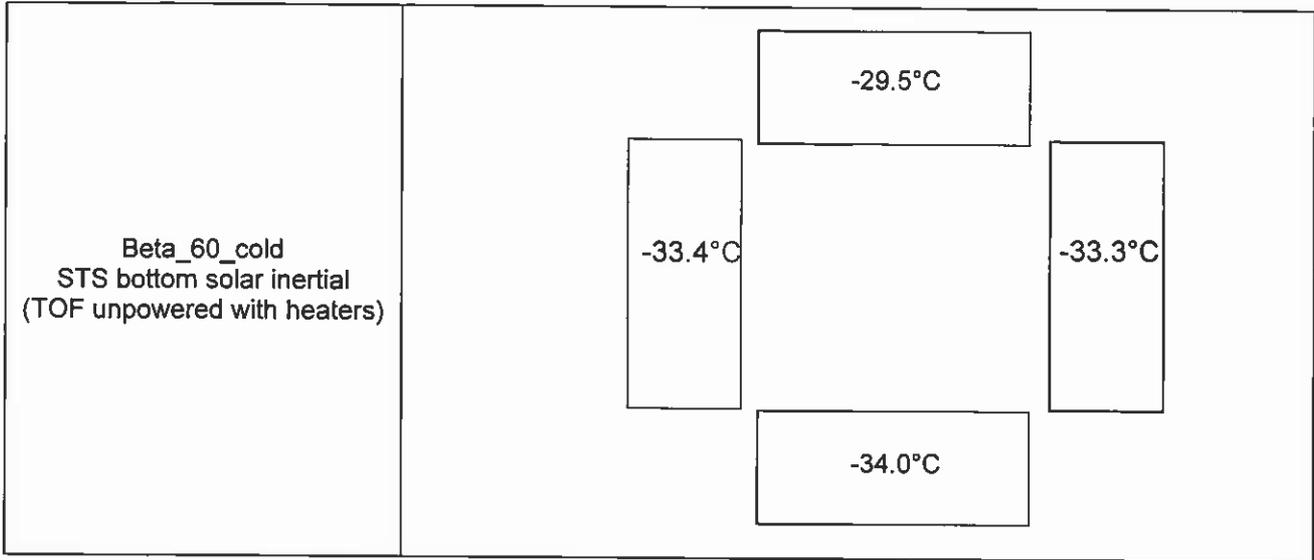
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Tab. 8-6 Temperature predictions for PMTs in STS free flying worst cold condition (TOF unpowered with heaters)

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8.3.2 AMS IN THE STS, DOCKED TO THE ISS

At system level, it was evaluated which is the most demanding orbital conditions for the TOF inside the Space Transportation System (STS), when docked to the ISS. The coldest orbit is characterized by Beta=60° Y, P, R=0°, 0°, 0°, cold environment.

The AMS configuration is the following.

AMS mounted in the STS, docked to the ISS

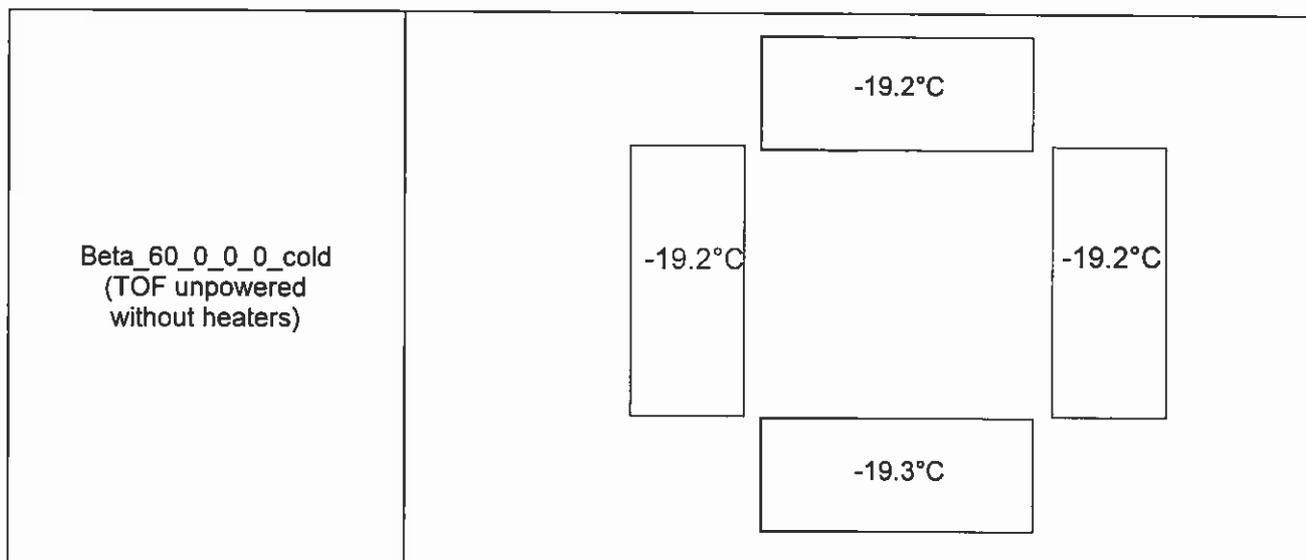
Coldest configuration

TOF power OFF

AMS power almost OFF (but the other heaters and the electronics needed to drive them)

The target is to keep the system above the MINIMUM NON OPERATIVE temperature on all the TOF PMTs.

According to the I/F data provided by the system, the minimum PMTs temperatures are shown in the following table, using the coordinate system shown in Fig. 8-1.



Tab. 8-7 Temperature predictions for PMTs in STS docked worst cold condition (TOF unpowered without heaters)

The minimum temperature along the PMTs is -19.3°C. This is far above the minimum non operative temperature of -40°C.

The conclusion is that no heaters are needed during the STS-docked phase.

8.3.3 AMS TRANSFER SEQUENCE

The position during the AMS-02 transfer phase from the STS to the ISS is characterized by an intermediate position (the HANDOFF, or the moment in which it is attached both to the STS and the ISS robotic arms). An appropriate description of the environment is provided (in the form of I/F data) by the system manager, for the worst orbital conditions for the TOF. It includes the complete transfer sequence, from the STS docked to the ISS installation. These phases include a limited (2 hrs) power off scenario during the handoff.

In that configuration (excluding during the 2 hours of "power off" at the hand-off), the power of most of the detectors shall be switched OFF, but for the HEATERS and the electronics needed to feed and measure them, and the electronics and the detectors already switched on. For a more precise description of the power configuration, see RD 2 (section 7.2).

The target is to keep the system above the MINIMUM NON OPERATIVE temperature on all the TOF PMTs.

According to the I/F data provided by the system thermal team, the temperature distribution along the TOF is given in the following picture: we start from the equilibrium solutions in the STS docked configuration, then we apply the 2+6 hours transient analysis.

The coldest orbit is characterized by Beta=-60° Y, P, R=0°, 0°, 0°, cold environment.

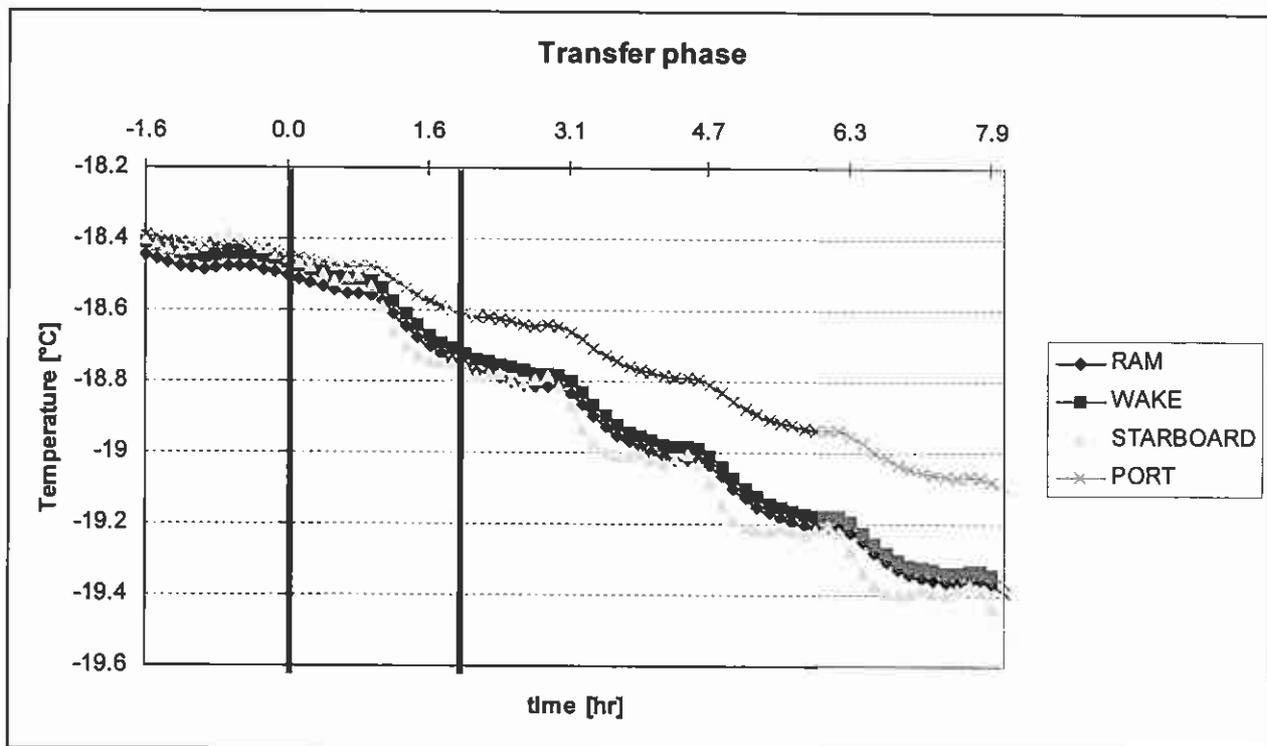


Fig. 8-2: temperature evolution of the TOF PMTs, during the transfer phase, with a 2 hours blackout (starting at the orange line) and a 6 hours powered conditions (non operative, starting at the green line)

The results show that the transfer phase is not critical from the thermal point of view; the minimum temperature reached by the coldest PMT is -19.5°C. The non operative requirements are fulfilled with broad margin.

The results above have been obtained with NO HEATERS and the detector switched OFF. As we shall see in the next sections, heaters will be present anyway, thus the temperatures presented above must be considered as a lower limit for the PMT temperature.

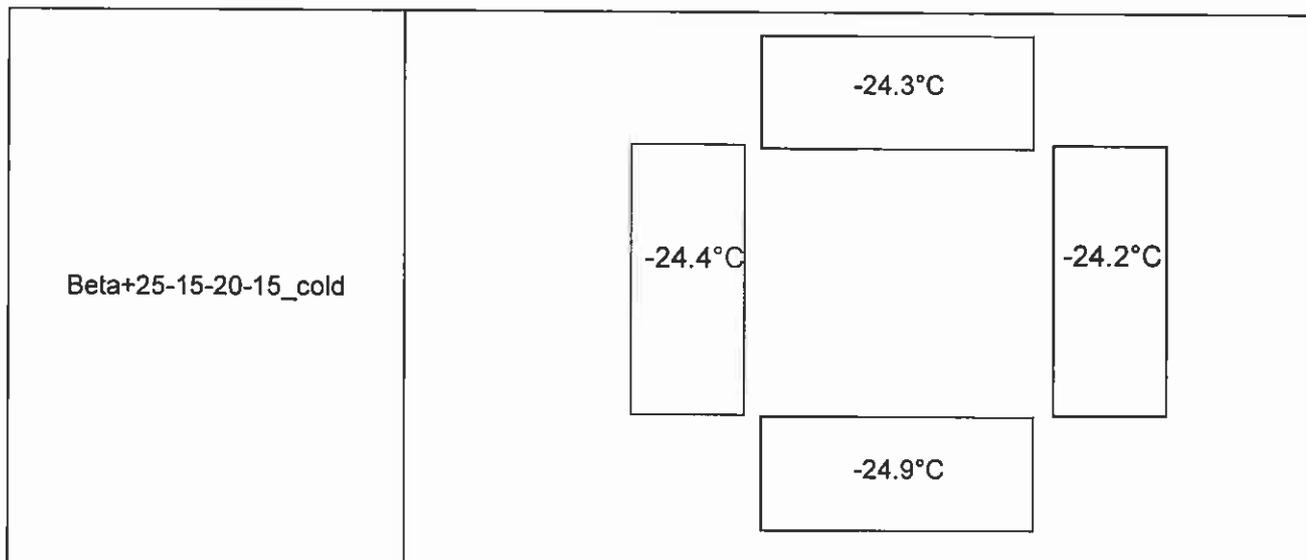
8.4 SWITCH ON HEATERS

The switch on heaters serve to carry the detector to the minimum switch on temperature when AMS-02 starts its operating procedure. The switch on heaters sizing is carried in the following configuration:

- AMS mounted in the ISS
- Coldest configuration
- TOF power OFF
- AMS power partially ON (namely, will be ON: the other detectors which will be switched on earlier, plus the survival heaters of the other subdetectors, plus the operating electronics units, such as the PDS, the main radiators heaters, etc)

The target is to reach the MINIMUM SWITCH ON temperature on all the TOF PMTs (namely -30°C).

When left without heaters, the TOF reaches a MINIMUM temperature equal to -24.9°C on the coldest PMT:



Tab. 8-8 Temperature predictions for PMTs worst cold condition on orbit (switch on condition)

The conclusion is that no heaters are needed to switch on the TOF.



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8.5 COOLING DOWN

The cooling down scenario is a contingency where the AMS-02 experiment is left unpowered for a maximum period of 8 hours. The model configuration in this case is the following

AMS mounted on the ISS
Coldest configuration
TOF power OFF
AMS power completely OFF

The starting point of the transient analysis is the stable behaviour at the coldest orbital case (namely $\beta = +25^\circ$, attitude $-15^\circ - 20^\circ - 15^\circ$) with AMS completely switched ON.

The target is to keep the system above the MINIMUM NON OPERATIVE temperature on all the TOF PMTs.

According to the I/F data provided by the system, the PMTs temperatures are shown in the following picture:

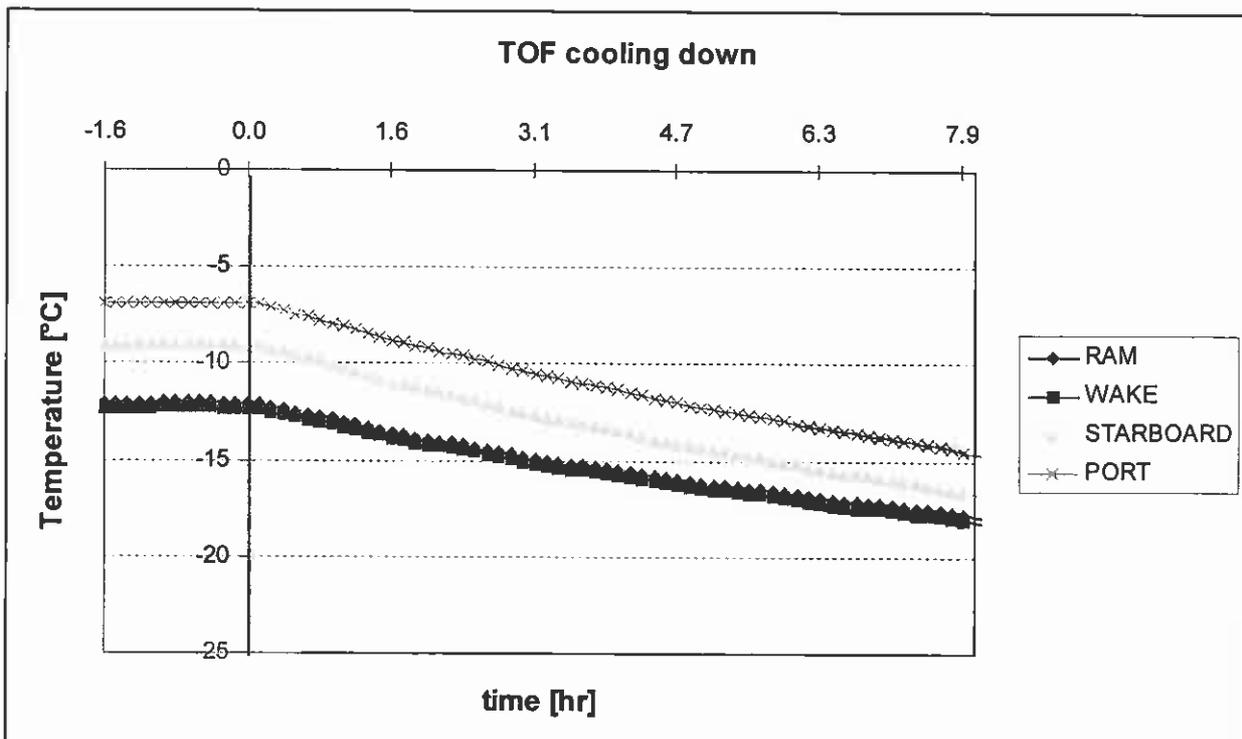


Fig. 8-3 PMT temperature during the cooling-down: starting from the worst cold environment, AMS-02 is switched off (orange line) and starts cooling.

The system shows a high thermal inertia, and after 8 hours the minimum PMT temperature is -18.2°C . The minimum non operative temperature requirements are fulfilled with large margins.

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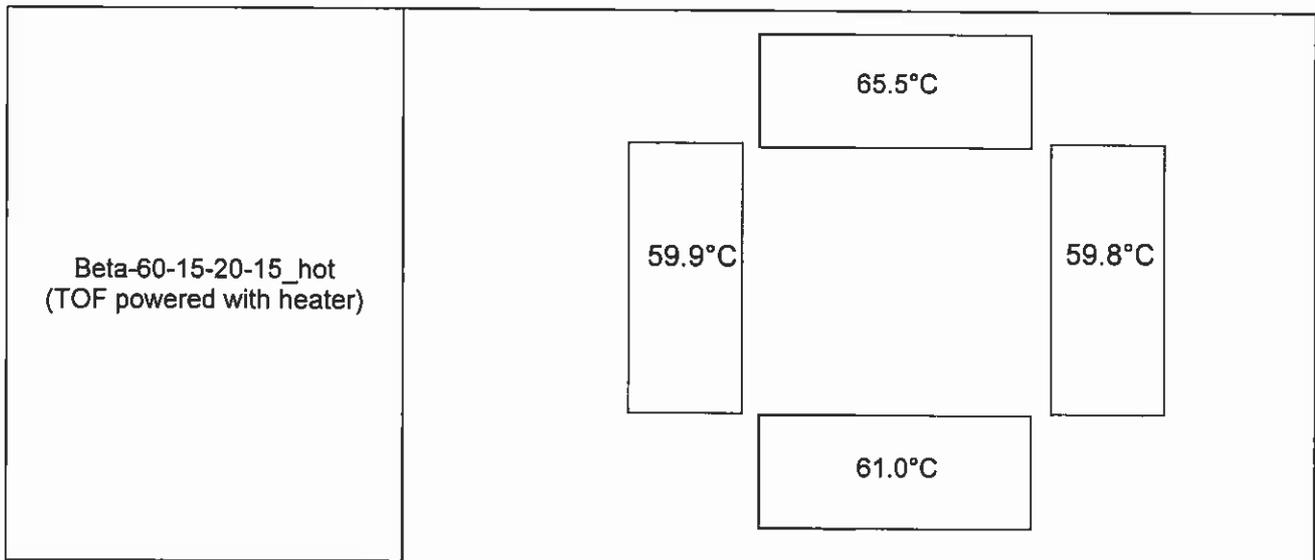
8.6 HEATERS FAILURE

In case of heaters failure, the system must not exceed the maximum touch temperature on the exposed parts, equal to 113°C..

The I/F data for the worst hot orbit (B-60-15-20-15_hot) were generated according to a scenario where the heaters fail in the ON configuration (10W applied on the boxes). At the same time, the internal TOF power dissipation was kept at the maximum rate.

The maximum temperature reached on the boxes is 64.4°C (the maximum PMT temperature, inside the detector, is 65.5°C), well below the maximum touch temperature (see **Errore. L'origine riferimento non è stata trovata.** And **Errore. L'origine riferimento non è stata trovata.**)

The system is not critical in terms of maximum touch temperature.



Tab. 8-9 Temperature predictions for PMTs worst hot condition on orbit (heaters failure)



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9. PORON INTRODUCTION IMPACTS

9.1 INTRODUCTION

PORON (Urethane foam) has been introduced among Lower TOF PMTs.

The effect of the thermal insulation properties of this foam needs to be investigated, to confirm the lower TOF Thermal Control System configuration. The following paragraphs describe the modelling and the results obtained at PMT level with its introduction.



Fig. 9-1 PORON foam introduced on Lower TOF PMTs.

9.2 PORON MODELLING

PORON foam is a thermal insulator and it is placed on the PMTs body. The heat is exchanged radiatively from their covering structure to the TOF box walls. In order to simulate PORON presence, the surfaces of the PMTs were disabled in the geometrical model, blocking the radiative heat flow from the insulated sides to the environment.

A thin copper layer, noticeable in the picture, has been placed around PMTs. This layer represents an additional insulation mean, being the emissivity of the copper very low, namely 0.02 (value used in the simulations). Therefore also this contribution to the overall radiative conductors has been considered. The emissivity of the PMTs box have been changed from black optical properties to copper layer ones.

9.3 ANALYSIS RESULTS

The following results are related to PMT boxes in +/- X direction.

A set of five different conditions is reported:

- 1) TOF PMT baseline design.
- 2) TOF PMTs are inactive in the geometrical model, simulating a full coverage of the PMT structure with PORON foam. This results in having no radiation heat exchange among PMTs and the surrounding box walls.
- 3) TOF PMTs are partially inactive, to consider only a part of the structure insulated by the PORON.
- 4) TOF PMTs partially inactive, as the case above, but the external optical properties are those of the copper layer.
- 5) TOF PMTs partially inactive, the external optical properties are those of the copper layer and in addition the PORON conductive links have been introduced (PORON conductivity being (0.076W/m/K).

Worst hot case TOF on ISS:

Beta=-75

Yaw, Pitch, Roll = -15, +15, +15 hot environment

		1	2	3	4	5
		Current design	PMT inactive	PMT partially inactive	PMT partially inactive + copper	PMT partially inactive +copper +Poron
-X (STRB)	average	46.5	57.6	49.1	51.9	49.6
	max	46.9	59.3	51.1	53.7	50.4
	min	45.6	55.6	47.1	50.5	48.8
+X(PORT)	average	40.6	51.5	42.7	45.8	43.3
	max	41.3	53.5	44.4	47.5	44.0
	min	39.8	49.3	41.1	44.7	42.8

Tab. 9-1 Temperatures on TOF PMT during orbital period in worst hot case

As the table reports, having the PMT completely inactive violates the requirements on PMTs maximum temperature limit. This means that the structure cannot be completely covered by PORON. Among analysis 3,4 and 5 the most conservative approach is to consider the PMT partially covered with PORON and shielded by the copper layer, without any contribution to the heat rejection coming from the conductive path across the PORON foam. Furthermore the introduction of the conduction contribution is not easily modelled because of not well known parameters like contact surface area and contact conductance at the IF between the PMT structure and the PORON.

The following picture shows the temperature during the orbit of the hottest box in the highlighted condition (4).



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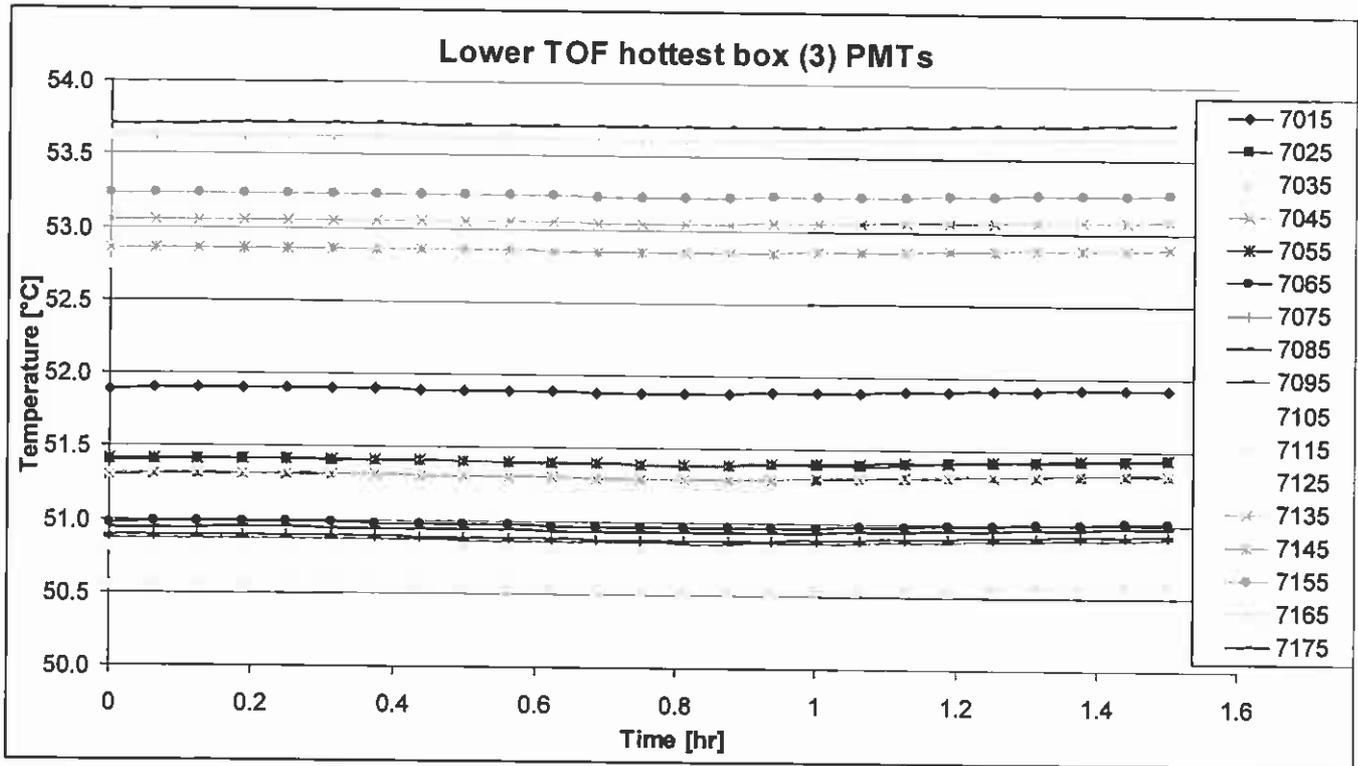


Fig. 9-2 Hottest box PMTs temperature in worst hot condition

Worst cold case TOF on ISS:

Beta=+25

Yaw, Pitch, Roll = -15, -20, -15 cold environment

		1	3	4	5
		Current design	PMT partially inactive	PMT partially inactive + copper	PMT partially inactive +copper +Poron
-X (STRB)	average	-14.0	-9.5	-4.7	-10.0
	max	-12.9	-5.5	-1.2	-8.9
	min	-15.7	-13.2	-7.0	-11.1
+X (PORT)	average	-13.3	-9.4	-4.2	-9.3
	max	-12.2	-6.3	-1.4	-8.4
	min	-14.7	-12.0	-5.8	-10.1

Tab. 9-2 Temperatures on TOF PMT during orbital period in worst cold case

In the worst cold case the reduced thermal links increases the margins on the minimum temperature limit. Therefore no issues arise in the cold analysis, confirming the PORON configuration defined for the worst hot case.

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10. CONCLUSIONS

The Thermal Mathematical and Geometric models of ToF have been described. Analysis results have been presented and they can be summarized as follows:

10.1 ON ORBIT ANALYSIS

Operative/non operative Hot cases

The performed runs show that positive margins exist for the operative cases but for the orbits

- B-75 MPA
- B-75-15+15-15
- B-70 MPA

In these cases the PMTs temperature is out of the maximum acceptable temperature (namely +50°C) as shown in the next table (+5°C of temperature uncertainty has been considered) :

	PMT maximum temperature prediction , °C	PMT maximum predicted Uncertainty , °C +	PMT temperature requirement, °C	Margin, °C
B-75 MPA	+60.6	+65.6	+55	-10.6
B-75-15+15-15	+62.2	+67.2	+55	-12.2
B-70 MPA	+52.4	+57.4	+55	-2.4
B-60-15-20-15	+50.2	+55.2	+55	-0.2
B-60 MPA	+41.0	+46.0	+55	+9.0

Tab. 10-1 Hot operative cases PMT temperature predictions and resulting margins

Due to the negative margins occurring in the beta angle range $\beta -70^\circ$ e $\beta -75^\circ$, independently on the attitude of the ISS, the TOF can not operate respecting the requirement.

Since the ISS stays only 5.6 days per year between $\beta -70^\circ$ e $\beta -75^\circ$, resulting in 1.5% of the entire mission duration, a possible recovery action is to switch off the ToF subsystem during these few days, without compromising the mission scientific goal.

The following table shows temperature predictions for the cases presented in Tab. 10-2 but considering non operative conditions:

	PMT maximum temperature prediction , °C	PMT maximum predicted Uncertainty , °C +	PMT temperature requirement, °C	Margin, °C
B-75 MPA	+51.4	+56.4	+60	+3.6
B-75-15+15-15	+53.1	+58.1	+60	+1.9
B-70 MPA	+42.6	+47.6	+60	+12.4

Tab. 10-2 Hot non operative cases PMT temperature predictions and resulting margins

The non operative runs show that the non operative PMT requirements are fulfilled for $\beta -75^\circ$ (both MPA and worst hot attitude).

Operative/non operative Cold cases

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The performed cold runs show that positive margins exist for the investigated operative/non operative cases:

	PMT minimum temperature prediction , °C	PMT minimum predicted + Uncertainty , °C	PMT temperature requirement, °C	Margin, °C
B_0_0_0_-15	-10.4	-15.3	-30	+14.7
B_0 MPA	-10.2	-15.2	-30	+14.8
B+25-15-20-15	-12.3	-17.3	-30	+12.7

Tab. 10-3 Cold operative cases PMT temperature predictions and resulting margins

	PMT minimum temperature prediction , °C	PMT minimum predicted + Uncertainty , °C	PMT temperature requirement, °C	Margin, °C
B_0_0_0_-15	-25.6	-30.6	-40	+9.4
B_0 MPA	-22.1	-27.1	-40	+12.9
B+25-15-20-15	-23.8	-28.8	-40	+11.2

Tab. 10-4 Cold non operative cases PMT temperature predictions and resulting margins

No need for heaters is envisaged.

10.2 OFF NOMINAL ANALYSIS

The analysis show that **10 W are needed** to fulfil the requirements (driven by the non-operational limits in the STS free flying phase). No heaters are envisaged during the other phases of the transfer (AMS in the Cargo Bay with the STS docked to the ISS and AMS in Hand-off position) and during the switch on of the detector. No problems are envisaged for a possible heaters failure and for 8 hours power outage.

10.3 PORON INTRODUCTION IMPACTS

It has been shown that PORON foam introduction is feasible if the covered surface is a limited part of the PMTs. The current PORON configuration has been analyzed showing positive margins both for hot and cold cases (under case ID #4). The copper shield introduced increases the temperatures because it limits the thermal rejection path, but it has been evidenced that the effect still keeps the PMT inside their temperature requirements.